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Chang et al.

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(54) **METHOD OF CONTROLLING BATTERY STATE USING CONSTANT-VOLTAGE DISCHARGE**

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H01M 10/44 (2006.01)
H01M 10/46 (2006.01)
H02J 7/00 (2006.01)

(52) **U.S. Cl.**
CPC ***H02J 7/00*** (2013.01)

(58) **Field of Classification Search**
CPC . H02J 2007/004; H02J 7/0031; H02J 7/0021; H02J 2007/0067; H02J 7/0078
USPC 320/127, 131, 132, 133, 135, 152, 157, 320/162
See application file for complete search history.

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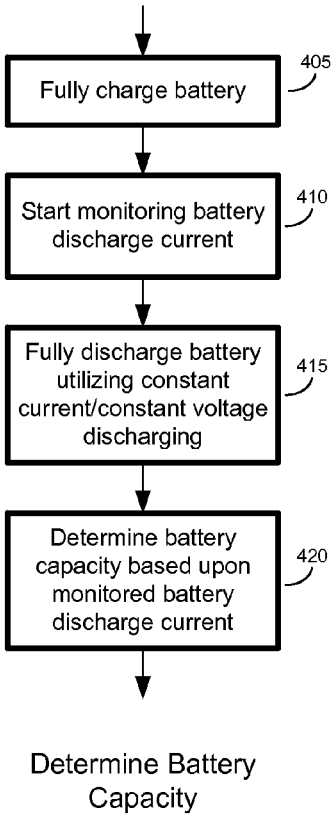
(57) **ABSTRACT**

A battery is rendered to a consistent discharged state in a two-phase battery discharge operation. In a first of the two discharge phases, a constant discharge current is drawn from the battery until a threshold battery voltage is reached. In the second of the two discharge phases, executed after the threshold battery voltage is reached during the first-phase, a time-varying discharge current is drawn from the battery at a constant battery voltage until a threshold discharge current is reached.

16 Claims, 4 Drawing Sheets



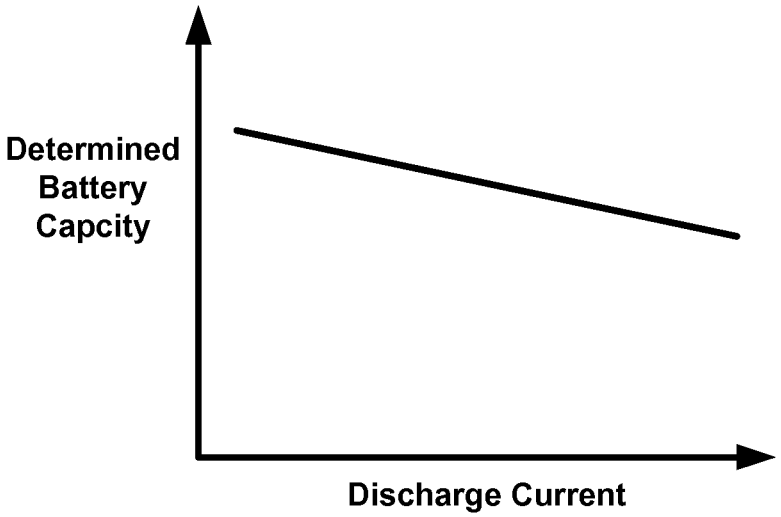


Figure 1A

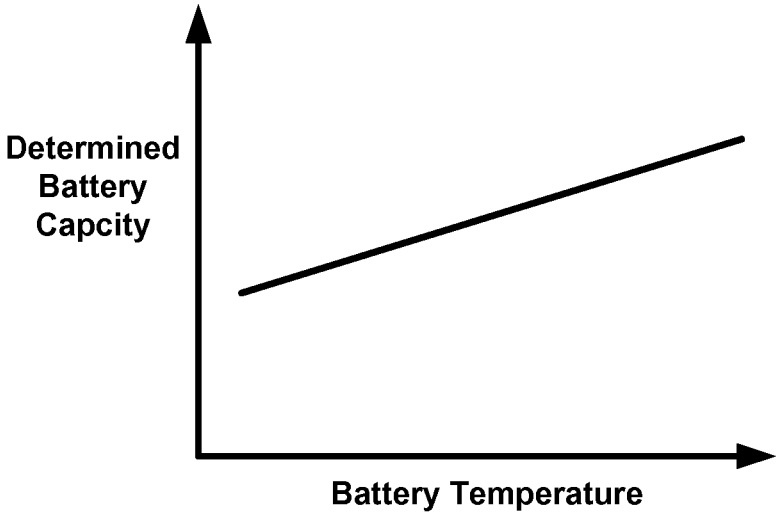


Figure 1B

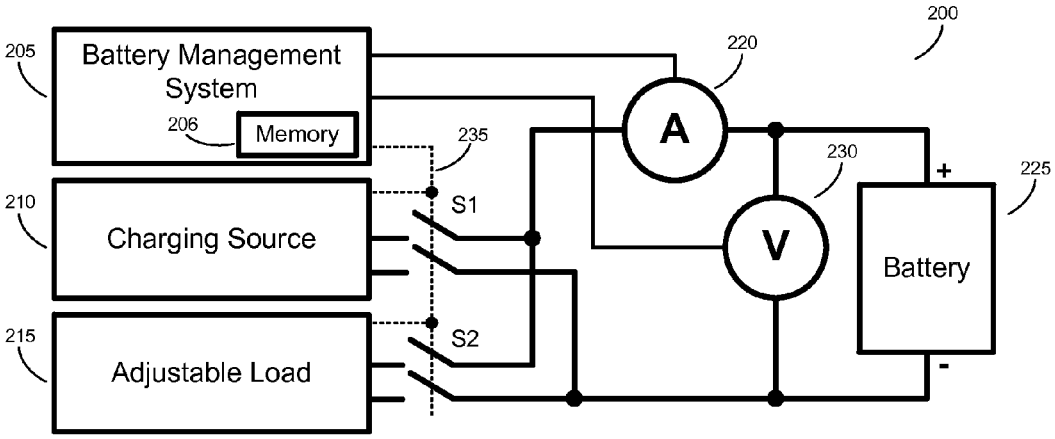


Figure 2A
Battery Capacity Determination System

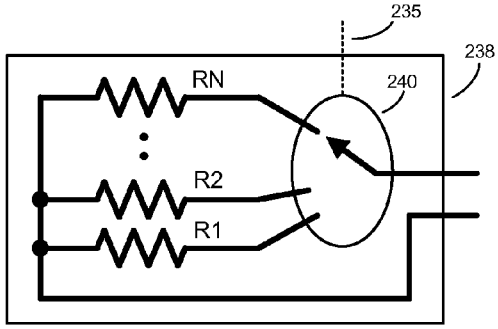


Figure 2B
Adjustable Load

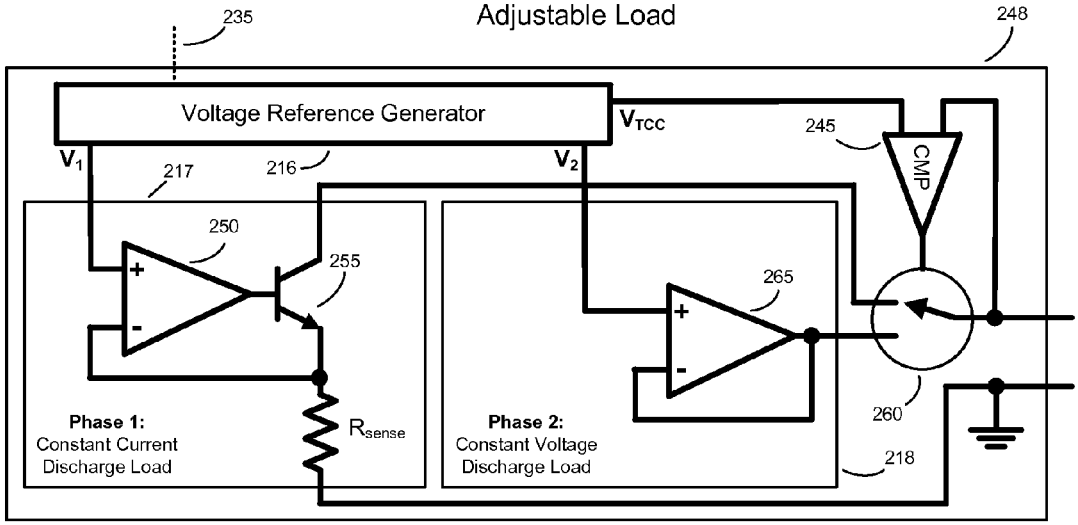


Figure 2C
Adjustable Load – Alternative Embodiment

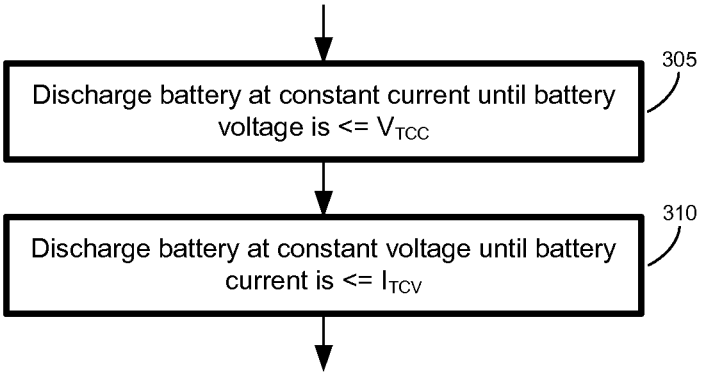


Figure 3A
Fully Discharge Battery

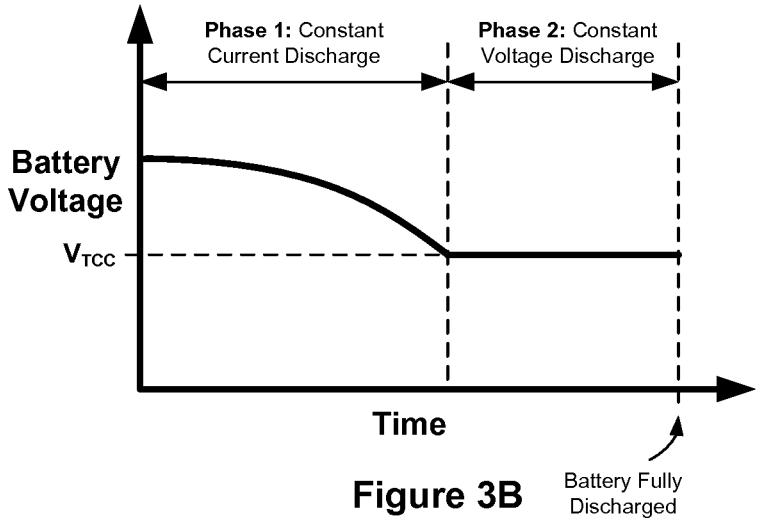


Figure 3B

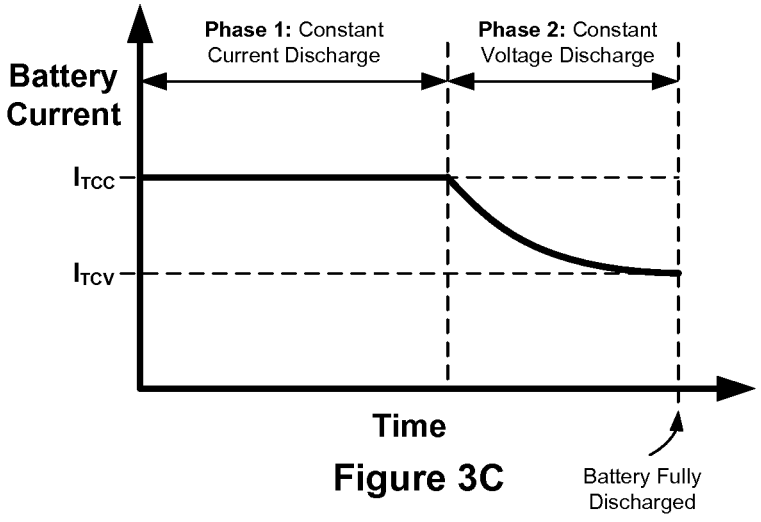


Figure 3C

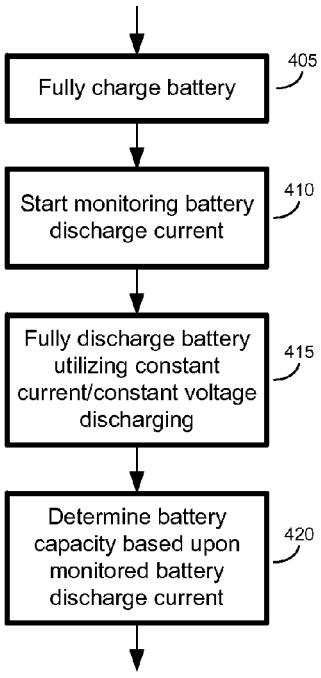


Figure 4A
Determine Battery Capacity

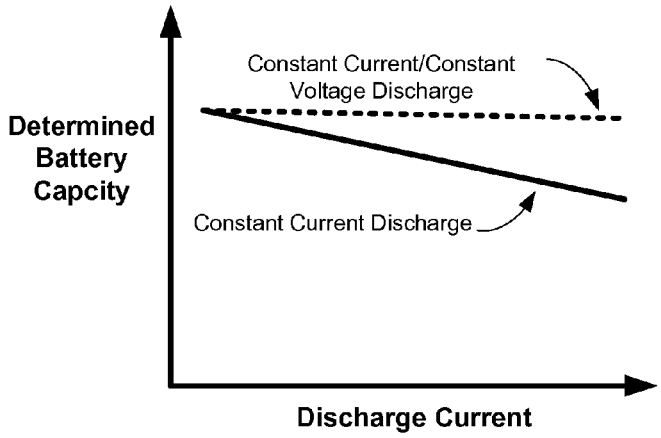


Figure 4B

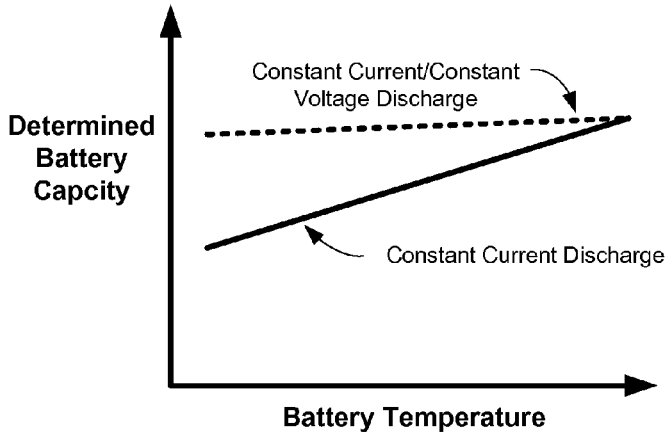


Figure 4C

METHOD OF CONTROLLING BATTERY STATE USING CONSTANT-VOLTAGE DISCHARGE

FIELD OF THE INVENTION

The present invention relates to rechargeable battery systems.

BACKGROUND

The fully-discharged or "empty" state of a rechargeable battery constitutes a reference point for determining a number of critical characteristics, including the full capacity of the battery as well as the charge remaining (i.e., state of charge (SOC)) following a period of use or dormancy. The SOC itself is typically applied to determine other important battery characteristics, including the DC resistance (DCR), a measure of wear that may be applied, in turn, to quantify the state-of-health of the battery.

Unfortunately, the conventional approach to establishing a fully discharged battery—discharging a fully-charged battery at a constant current for a predetermined time—tends to yield inconsistent results depending, for example on the discharge current rate and battery temperature, as illustrated conceptually in FIGS. **1**A and **1**B.

BRIEF DESCRIPTION OF THE DRAWINGS

The present invention is illustrated by way of example, and not limitation, in the figures of the accompanying drawings and in which like reference numerals refer to similar elements and in which:

FIG. **1**A is an exemplary diagram showing the relationship between the battery discharge current and the determined battery capacity when conventional techniques are used to discharge the battery;

FIG. **1**B is an exemplary diagram showing the relationship between the battery temperature and the determined battery capacity when conventional techniques are used to discharge the battery;

FIG. **2**A illustrates one embodiment of circuitry capable of determining the capacity of a battery;

FIG. **2**B illustrates one embodiment of circuitry capable of providing an adjustable battery load;

FIG. **2**C illustrates an alternative embodiment of circuitry capable of providing an adjustable battery load;

FIG. **3**A shows an exemplary sequence of operations for fully discharging a battery;

FIG. **3**B is an exemplary diagram showing the relationship between battery voltage and time during a battery discharge process utilizing the techniques described herein;

FIG. **3**C is an exemplary diagram showing the relationship between battery current and time during a battery discharge process utilizing the techniques described herein;

FIG. **4**A shows an exemplary sequence of operations for determining the capacity of a battery;

FIG. **4**B is an exemplary diagram showing the improvement in the consistency of the determined battery capacity across different battery discharge currents when the battery discharge process utilizes the techniques describe herein; and

FIG. **4**C is an exemplary diagram showing the improvement in the consistency of the determined battery capacity across different battery temperatures when the battery discharge process utilizes the techniques describe herein;

DETAILED DESCRIPTION

In various embodiments disclosed herein a battery pack is fully discharged to a consistent state by utilizing a two phase discharge process. During the first phase the battery is discharged at a constant current with the battery voltage decreasing until the battery voltage reaches a predetermined threshold. Next, during the second phase, the battery is discharged at a constant voltage with the battery current decreasing until the battery current reaches a predetermined threshold indicating a fully discharged battery. Through this two phase process, variations in the amount of charge actually remaining in the battery (i.e. the fully discharged state of the battery) may be reduced, particularly when the process is conducted under varying operating conditions such as different discharge currents and battery temperatures. This more consistent discharge state allows, in turn, for more accurate determination of battery capacity, state of charge, DC resistance (DCR), state of health and so forth. Additionally, compared to conventional single-phase techniques (using only a constant current discharge phase), the battery discharge process may occur more quickly and without the battery achieving voltage limits that may compromise battery life, safety, and other factors.

FIG. **2**A illustrates an embodiment of battery capacity determination system **200**. As shown, battery capacity determination system **200** comprises a battery management system **205**, a charging source **210**, an adjustable load **215** (shown in FIGS. **2**B and **2**C and described in more detail below), a current measuring device **220**, a voltage measuring device **230**, a battery **225** (for which the capacity is being determined) and two switches, S**1** and S**2**, which are used to electrically couple the charging source and the adjustable load respectively to the battery. S**1** and S**2** are controlled (i.e. opened and closed) under the control of the battery management system via control network **235**, which may also be used to control the charging source and the adjustable load. The battery management system, which may be used to execute the sequence of operations shown in FIGS. **3**A and **4**A, includes a memory **206** (to store information generated from the charging/discharging process and software code and data associated with executing the sequence of operations in FIGS. **3**A and **4**A) and may be implemented at least in part by a programmed processor. Other embodiments, which may comprise multiple batteries, may utilize more than one current and/or more than one voltage measuring device to monitor the charging/discharging process.

FIG. **2**B illustrates an embodiment of an adjustable load circuit **238** that may be used to implement adjustable load **215**. In the implementation shown, one of a plurality of resistors with different impedances (R**1** though RN) is electrically coupled to the battery through switch **240** operated via the control network **235** to provide N different possible loads to the battery. When utilizing the embodiment of the adjustable load shown in FIG. **2**B, the battery management system monitors the current flowing to/from the battery using the current measuring device **220** and the voltage across the battery using the voltage measure device **230**. Both the battery current and voltage can be controlled as required by the battery management system via the control network. For example, if a larger battery current is required, a resistor with lower impedance can be selected within adjustable load circuit **238** by sending the appropriate control signal or command through the control network to switch **240**. Similarly, if a higher battery voltage is required, a resistor with higher impedance can be selected using the switch **240**. Another embodiment of the adjustable load comprises a variable resistor (e.g., a rheostat) in place of the plurality of resistors.

FIG. **2**C illustrates an alternative adjustable load circuit **248** that may be used to implement adjustable load **215** of FIG. **2**A. As shown, adjustable load circuit **248** includes a

voltage reference generator **216** to control the voltages and currents during discharging, circuitry **217** for generating a constant current load during phase 1 of the discharge, circuitry **218** for generating a constant voltage load during phase 2 of the discharge, a switch **260** to select between the phase 1 circuitry **217** and phase 2 circuitry **218**, and a comparator **245**, which generates the signals necessary to cause switch **260** to electrically couple the phase 1 circuitry when the battery voltage is above V_{TCC} and to electrically couple the phase 2 circuitry when the battery voltage is equal to or below V_{TCC}.

The phase 1 circuitry **217** shown in FIG. **2**C comprises an operational amplifier **250**, variable-load transistor **255**, and a current sensing resistor, R_{SENSE}. If the phase 1 circuitry **217** is coupled to the battery via switch **260**, the discharge current flowing from the battery and through R_{SENSE} will create a voltage across R_{SENSE} that is compared, by the operational amplifier, to the voltage V_1. The voltage V_1 is generated by the voltage reference generator **216** based on control inputs from the battery management system via the control network **235**. If the voltage across R_{SENSE} is lower than V_1, then the operational amplifier will increase the control voltage at the base of transistor **255**, driving transistor **255** toward a higher conductance (lower impedance) state, causing more current to flow from the battery and through R_{SENSE} until the voltage across R_{SENSE} increases to become similar to V_1. Likewise, if the voltage across R_{SENSE} is higher than V_1, then the operation amplifier will drive transistor **255** toward a lower conductance state, causing less current to flow from the battery and through R_{SENSE} until the voltage across R_{SENSE} decreases to become similar to V_1. When the voltage across R_{SENSE} is similar to V_1, then the discharge current from the battery is approximately V_1/R_{SENSE}. Thus the discharge current for the battery can be controlled by varying the voltage V_1. If V_1 is held constant, then the battery discharge current will be held approximately constant, as required during phase 1 of the discharge. While the embodiment shown in FIG. **2**C utilizes a bipolar-junction transistor, a field effect transistor or other signal-controlled structure capable of serving as a variable load element may be used in alternative embodiments.

The phase 2 circuitry **218** shown in FIG. **2**C comprises an operational amplifier **265** configured to act as a buffer (or voltage follower). In this configuration, the output voltage of the operational amplifier is held approximately equal to the input, in this embodiment V_2. The function of the operational amplifier is to provide adjustable current sink capacity at an output voltage approximately equal to the input voltage. Thus, if the phase 2 circuitry **218** is coupled to the battery via switch **260**, the battery voltage will be held at a voltage approximately constant similar to V_2 by the operational amplifier, as required for phase 2 of the discharge, and the discharge current from battery should adjust (normally decrease) to maintain that voltage. The discharge current flows from the battery into operational amplifier **265** and to ground via the operational amplifier's unshown negative supply rail. The voltage V_2 is generated by the voltage reference generator **216** based on control inputs from the battery management system via the control network **235**. The voltage V_2 will nominally be set to be equal to V_{TCC} (in which case the battery will discharge at the constant voltage V_{TCC}) but in no case will V_2 be set to be greater than V_{TCC} during battery discharging (or the battery would begin to charge through the operational amplifier **265**).

As can be appreciated from the foregoing, operational amplifiers **250** and **265** enable relatively precise and continuous control over the voltage and current during the discharge process, mitigating the dithering effect that may occur in the embodiment of FIG. **2**B (e.g., as that circuit switches back and forth between two resistance values) and also avoiding voltage/current spikes that may occur during load switching. Note that the embodiment shown may be modified in numerous ways while generally maintaining the operational behavior described above. For example, a single operational amplifier may be switched between two different output/feedback arrangements corresponding to those shown in circuits **217** and **218**.

FIG. **3**A shows an exemplary sequence of operations for fully discharging a battery. This sequence shows the two phases of the discharge process. At **305**, the battery is discharged at a constant current of I_{TCC} (as controlled by the adjustable load **215**) until the battery voltage is less than or equal to V_{TCC}. After the battery voltage has reduced down to V_{TCC}, the battery is then discharged at a constant voltage of approximately V_{TCC} (again controlled by the adjustable load **215**) until the battery current is reduced to become equal to or less than I_{TCV}, at which point the battery is deemed to be "fully discharged".

In one embodiment V_{TCC}, I_{TCC} and I_{TCV} are predetermined and fixed. In other embodiments they may be dynamically calculated based on the current system operating conditions and/or based upon factors including, but not limited to battery age, discharge cycles, temperature and so forth.

The exemplary diagrams shown in FIG. **3**B and FIG. **3**C illustrate the relationship between battery voltage, battery current and time during the battery discharge process described herein. During phase 1, the discharge current is held constant approximately equal to I_{TCC} and the battery voltage decreases until it becomes less than or equal to V_{TCC}, at which time phase 2 begins. During phase 2 the battery voltage is held constant approximately equal to V_{TCC} until the decreasing battery discharge current becomes equal to or less than I_{TCV}, at which point the battery is deemed to be "fully discharged".

FIG. **4**A shows an exemplary sequence of operations for determining the capacity of a battery utilizing the techniques for discharging a battery described herein. Beginning at **405** the battery is fully charged. One embodiment may first charge the battery using a constant current until a predetermined voltage is reached and then second charge the battery using a constant voltage gradually decreasing the charging current until a predetermined current is reached. Other embodiments may use different techniques to fully charge the battery. Next, at **410**, the battery management system begins monitoring (or accumulating a measurement or count of) the battery discharge current. In one implementation, for example, as the battery discharges, the number of coulombs delivered by the battery is counted and totaled until the battery is fully discharged under the two-phase constant-current/constant-voltage discharge technique described above (i.e., as shown at **415**). At **420**, the battery capacity is determined based on the monitored battery discharge current, for example by recording the net accumulated charge as the capacity of the battery, by indexing a table of battery capacities using the net accumulated charge (and possibly other parameters, such as average temperature during discharge), by comparing the net accumulated charge against one or more prior accumulated charge measurements to revise a previously recorded battery capacity measurement, etc.

FIG. **4**B shows an exemplary diagram illustrating the improvement in the consistency of the determined battery capacity across different battery discharge currents when the battery discharge process utilizes the techniques describe herein. When the battery capacity is determined using only a constant current discharge technique (i.e. replacing the two-phase discharge approach shown in operation **415** of FIG. **4**A

with a single-phase constant current discharge process), the battery capacity determination is shown by the sloped solid line, yielding a varying capacity measurement (higher or lower) depending on the level of discharge current used to discharge the battery, and thus, a potentially inconsistent, less accurate determination of the actual battery capacity. If, however, the two-phase discharge approach described above and shown at **415** of FIG. **4**A is utilized, a relatively consistent, more accurate battery capacity determination is achieved, despite variation in battery discharge current.

Similarly, FIG. **4**C shows an exemplary diagram illustrating the improvement in the consistency of the determined battery capacity across different battery temperatures when the battery discharge process utilizes the techniques describe herein. When the battery capacity is determined using only a constant current discharge technique (i.e. replacing the two phase discharge process used in operation **415** of FIG. **4**A with a single phase constant current discharge process), the battery capacity determination is shown by the solid line, increasing as the battery temperature increases. Thus, for the same battery, varying battery capacities may be determined that depend on the battery temperature during the battery capacity determination process. Again, this results in an inconsistent and less accurate determination of the actual battery capacity. If, however, the two-phase discharge approach described above and shown at **415** of FIG. **4**A is utilized, the battery capacity determination is shown by the dashed upper line, where the determined battery is more consistent and therefore more accurate over different battery temperatures.

In the foregoing description and in the accompanying drawings, specific terminology and drawing symbols have been set forth to provide a thorough understanding of the present invention. In some instances, the terminology and symbols may imply specific details that are not required to practice the invention. For example, the term "coupled" is used herein to express a direct connection as well as a connection through one or more intervening circuits or structures. Device or system "programming" may include, for example and without limitation, loading a control value into a register, one-time programmable-circuit (e.g., blowing fuses within a configuration circuit during device production) or other storage circuit within an integrated circuit device of the host system (or host device) and thereby control an operational aspect of the host system or establish a host system configuration. The terms "exemplary" and "embodiment" are used to express an example, not a preference or requirement. Signal paths that appear as single conductors may include multiple conductors and vice-versa, and components shown as being included within or forming part of other components may instead be disposed separately from such other components. With regard to flow diagrams and the like, the order of operations may be different from those shown and, where practical, depicted operations may be omitted and/or further operations added.

While the invention has been described with reference to specific embodiments thereof, it will be evident that various modifications and changes may be made thereto without departing from the broader spirit and scope. For example, features or aspects of any of the embodiments may be applied, at least where practicable, in combination with any other of the embodiments or in place of counterpart features or aspects thereof. Accordingly, the specification and drawings are to be regarded in an illustrative rather than a restrictive sense.

What is claimed is:

1. A method of rendering a battery to a discharged state, the method comprising:

drawing a constant discharge current from the battery until the battery voltage falls below a threshold voltage level; and

after the battery voltage falls below the threshold voltage level, drawing a time-varying discharge current from the battery while (i) maintaining the battery voltage at a predetermined constant voltage and (ii) the time-varying discharge current remains above a threshold current level, the battery being deemed to be in the discharged state after the time-varying current falls to the threshold current level.

2. The method of claim **1** wherein drawing the constant discharge current from the battery until the battery voltage falls below the threshold voltage level comprises switchably coupling the battery to a time-varying load impedance and varying the time-varying load impedance as necessary to maintain the constant discharge current.

3. The method of claim **2** wherein varying the time-varying load impedance comprises switchably coupling two or more of a plurality of resistors between terminals of the battery at respective times.

4. The method of claim **2** wherein varying the time-varying load impedance comprises switchably coupling a transistor to the battery between terminals of the battery, the transistor having a control input coupled to an output of a feedback circuit.

5. The method of claim **1** wherein drawing a time-varying discharge current from the battery comprises switchably coupling the battery to a time-varying load impedance and varying the time-varying load impedance as necessary to maintain the constant discharge voltage.

6. The method of claim **5** wherein varying the time-varying load impedance comprises switchably coupling two or more of a plurality of resistors between terminals of the battery at respective times.

7. The method of claim **5** wherein varying the time-varying load impedance comprises switchably coupling an operational amplifier configured as a voltage follower to the battery.

8. The method of claim **1** further comprising accumulating a value corresponding to a total amount of current discharged from the battery while drawing the constant discharge current from the battery, and while drawing the time-varying discharge current from the battery.

9. The method of claim **8** further comprising determining the capacity of the battery based upon, at least in part, the value corresponding to the total amount of current discharged from the battery.

10. An apparatus for discharging a battery, the apparatus comprising:

discharge circuitry operable in either a constant-current mode to draw a constant discharge current from the battery while allowing a time-varying battery voltage, or in a constant-voltage mode to draw a time-varying discharge current from the battery while maintaining a battery voltage at a predetermined constant voltage; and

control circuitry to operate the discharge circuitry in the constant-current mode until the battery voltage falls below a threshold voltage level and, after the battery voltage falls below the threshold voltage level, to operate the discharge circuitry in the constant-voltage mode until the time-varying current falls below a threshold current level.

11. The apparatus of claim **10** wherein the discharge circuitry comprises time-varying load impedance circuitry capable of varying the time-varying load impedance as necessary to maintain the constant discharge current in the con-

stant-current mode and capable of varying the time-varying load impedance as necessary to maintain the battery voltage at the predetermined constant voltage in the constant-voltage mode.

12. The method of claim **11** wherein the time-varying load impedance circuitry comprises a plurality of resistive elements.

13. The method of claim **11** wherein the time-varying load impedance comprises an operational amplifier having an output coupled to a control input of a transistor.

14. The method of claim **11** wherein the time-varying load impedance comprises an operational amplifier configured as a voltage follower.

15. The apparatus of claim **10** further comprising circuitry to accumulate a value corresponding to a total amount of current discharged from the battery while the discharge circuitry operates in the constant-current mode and in the constant voltage mode.

16. The apparatus of claim **10** further comprising circuitry capable of determining the capacity of the battery based upon, at least in part, the value corresponding to the total amount of current discharged from the battery.

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